DESIGN OF INJECTORS FOR SELF-SUSTAINING OF COMBUSTION CHAMBERS ACOUSTIC STABILITY

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Abstract

Comparative analysis of the injector development history in order to eliminate acoustic instability in combustion chambers of LOX/kerosene big thrust engines both of gas generator and staged combustion cycle such as F-1, RD-170 and some experimental engines is presented in the Paper. It was studied what stationary and dynamic parameters of injector elements and the injector assembly as a whole were changed during such a development and what kind of influence on instability they provided. It was discovered that in every case of successful efforts to achieve stability, alongside with the decreasing of amplification qualities of the combustion zone by means of decreasing atomization and mixing efficiency that decreased to some extend combustion chamber specific impulse, increasing acoustic losses in the combustion chamber by means of installation of baffles and/or acoustic cavities, injectors in stable operated combustion chambers provided self-sustaining of the operational process, which under the influence of pulsation amplitude provided decreasing of the combustion zone amplification qualities. Methods of instability mechanisms diagnostics and instability elimination by means of changing of injector dynamic characteristics are proposed and compared with the results of fire tests in model combustion chamber. Some useful expressions are presented in the Paper to define dynamic characteristics of jet and swirl injectors as well as interference of swirled fuel flow with the central Ox-rich gas stream.

Nomenclature

A – geometrical characteristics of swirl injector
a - relation between free area of closed side of swirl injector and area of its nozzle
C – arbitrary constant
D – diameter of an element
d – diameter of a substance (drop, spray)
e = 2.71828…
F – flow area
f – frequency
f( ) - functional dependence
h – liquid film thickness
Im – imaginary part of a function of complex argument
i – imaginary unit
j – centrifugal acceleration
L – length of an element
M - mass
p – pressure
Q – volumetric flow rate
q – tangent of the nozzle surface inclination to the injector axis

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R – radius of an element
Re - Real part of a function of complex argument
r – radius of the flow
S- surface
Sh – Stroughal criterion
t – time
U – general velocity of the flow
W – component of the velocity
x – coordinate
< > - characteristic value

Greek letters

$\boldsymbol{\alpha}$ – angle of the spray
$\boldsymbol{\beta}$ – degree coefficient in the expression (43)
$\boldsymbol{\Delta}$- increment, difference
$\boldsymbol{\lambda}$- wave length
$\boldsymbol{\mu}$ – viscosity
$\boldsymbol{\mu_i}$ – discharge coefficient
$\boldsymbol{\nu}$ – viscous decrement
$\boldsymbol{\Pi}$- response function
$\boldsymbol{\pi}$= 3,14…
$\boldsymbol{\rho}$ – density
σ – surface tension
$\boldsymbol{\Phi}$ – shift angel of a separate element
φ – a part of swirl injector nozzle filled by liquid
$\boldsymbol{\Psi}$- shift angle of an element in their integrity
$\boldsymbol{\Omega}$- amplitude of surface waves
$\boldsymbol{\omega}$ – circular frequency

Indexes

a – axial
ag – gaseous atomization
c – chamber
div – divergent
ex – exit
g – gas
in – inlet
k – closed section
l – liquid
m – vortex surface
n – nozzle
r – radial
T – tangential
u – circumferential

v – vortex
w – wave
Σ – total value
0 – initial conditions
1,2… - number of models
32 – Zauter's
∞ - infinite value

1. Injection of propellants in combustion chamber and its role in the LRE operational process

1.1. The role of propellant's injection in the formation of combustible mixture

Organization of propellants injection in a combustion chamber has predominant influence on combustion efficiency and stability. In combustion technology there exist several methods of combustible mixture formation:

3.┌ . by means of mixing both oxidizer and fuel in liquid phase without any atomization (mainly for hypergolic propellants),

b) by means of evaporation or decomposition of liquid propellant and its mixing with another one in gaseous state,

c) by means of foaming of liquid propellant by gaseous one, i.e. by atomizing of gas particles in liquid flow (mainly in very high pressures when gas density is enough high and requires not too high relation of gas and liquid volumes),

d) by atomizing of liquid propellant and mixing it with gaseous one in the form of plurality of droplets.

The last one have the most spread and is mainly used in gas turbine and other air breathing engines, and in main combustion chambers of Liquid-propellant Rocket Engines (LRE) having oxidizer-rich staged combustion cycle. Stationary characteristics of injector such as mean median droplet diameter D_{32}, spectrum of droplets, concentration of droplets via cross section of the gas-liquid flow – define both stationary and dynamic characteristics of combustion (its completeness, spreading of the combustion zone, specific heat release per unit of volume; time lag of combustion and its response on occasional fluctuations of pressure, velocity and vorticity, etc., and sequent its efficiency and stability.

1.2. Conditions of propellants injection and mixing in LRE

Conditions for injection of propellants and for preparation of combustible mixture in LRE have some peculiarities comparatively to industrial burners. These peculiarities rather

simplify to some extend the problem of combustible mixture preparation, but apply some additional problems that must be taken into account when designing high pressure LRE.

-High pressure in combustion chamber and in propellant's feed lines. For liquid propellants it is nice as it eliminates or decreases the danger of cavitation erosion in injectors comparatively to jet engines, increase temperature margins for heating of liquid propellant. As to gaseous one, its density increases and such parameter strongly increase the interaction of gas and liquid, improve atomization velocity and propellants mixing. Therefore, injectors in high-pressure ox-rich stage cycle combustion chambers are not obliged to form too small droplets as it is required in jet engine combustion chamber, because it will lead to their too quick combustion near by or even inside injectors, their overheating or even out-burning. The main obligation of such injectors is in required evenness of propellants mixing in order to be burnt with high combustion completeness. Another and very significant obligation of gas-liquid injectors is to provide low sensitivity of combustion zone to pressure and other fluctuations in the combustion zone, for which neighbor injector elements in multi-injector assembly must have a bit different stationary and dynamic characteristics in order to form combustion zone with uneven spreading of heat release per thickness of the combustion zone and, more less, across the flow. Even slight deviation of O/F ratio from injector to injector that have very weak effect on combustion efficiency, strongly decrease the sensitivity of the combustion zone and its ability to respond and amplify pressure pulsation.

-Relatively to other combustors, low pressure drop, applied to injectors (relatively to combustion chamber pressure). Usually, the mean value is about 10% from Pc. The lower pressure drop – the higher efficiency of the whole LRE operational process. This circumstance leads to high sensitivity of any LRE injector to combustion chamber pressure variation: slight, only 2% of combustion pressure variations mean 20% of pressure drop variations, applied to injectors. Variations of Pc more than 10% lead to the penetration of hot products of combustion into propellant feed lines that usually ends by engine explosion. Therefore, special means must be used to provide smooth going to nominal regime without strong picks of pressure.

-Cryogenic, very active and even self-ignitable propellants. Chemical energy, accumulated in LRE propellants, is sufficiently higher than in the pair "air – kerosene", and therefore presence of previously mixed, ready but not yet burnt combustible mixture comprise very dangerous condition. We have rather contradictive requirements: to premix propellants in order to get high combustion efficiency and not to premix in order to provide reliability – is a typical problem for LRE combustor designers. It can be solved by very quick mixing and immediate burning directly after combustible mixture formation.

-High level of noise, vibration and other oscillations that accompany LRE combustion. Roaring of flame, screaming of turbulent flows, high vorticity in separation zones create high level of acoustic pulsation. Therefore, mechanisms of liquid droplet formation and atomization, described theoretically and studied experimentally in steady conditions and really existing in ambient conditions do not realized in LRE. Most of

estimations taken from numerous books give wrong values of atomization parameters and cannot be used for LRE. Really, LRE designers are disarmed before the problem of proper calculation of atomization; they use very approximate expressions with a lot of empirical coefficients.

-High heat flux in the atomization and mixing zones – due to heat release zone situated closely or even inside injector, that lead to partial evaporation of droplets and liquid films. This cannot be neglected in theoretical and experimental studies.

1.3. The role of the injector as a part of the engine as a dynamic system

Let us consider the simplest scheme of LRE with pressurized propellant feed system, connected with the combustion chamber by an injector. Pulsation of pressure in the combustion chamber of such a LRE , as it was shown in [1], will influence the combustion zone by means of feedback connection (1) (see Fig. 1a.), and combustion will respond to these excitations according to multiplicity of mechanisms, described in a lot of publications, dedicated to high frequency combustion instability (see, for instance, [2]). Simultaneously, pressure pulsation will influence propellant injectors by means of feedback connection (2) and excite pulsation of mass flow rate, velocity and other output parameters. Mass flow rate pulsation will excite oscillations in feed lines by means of feedback connection (3). Both pulsation of pressure in feed lines and in the combustion chamber will form pressure drop pulsation applied to injectors by direct connection (4). As a result, pulsation of propellants mass flow rate, dispercity of droplets, spray angle and oxidizer-to-fuel ratio pulsation in the combustion zone will occur, that can result in the pulsation of heat release and secondary pressure pulsation in the combustion chamber, where at least two mechanisms of acoustic instability will exist: one due to direct response of the combustion zone on pressure pulsation, another – due to the injector response to the pressure drop pulsation. Whether the injector response is significant or not for high frequency combustion instability depends on the dynamic characteristics of injection, mainly on the module of the injector response function.

Studies of dynamic characteristics of liquid injectors showed that for usual injectors this response is high enough up to frequencies about several thousand Hertz [3], causing strong flow oscillation in outflow jets. Swirl injectors studies showed that they have not only high response, but provide significant shift angle between the input pressure drop oscillations and mass flow rate oscillations in the cone of atomized liquid, accompanied by strong spray angle pulsation [4]. Some methods were found to decrease or even totally eliminate the sensitivity of liquid injectors to pressure drop pulsation [5], that allowed to use such injectors in combustion instability research.

In the LRE with staged combustion cycle that have combustion chamber with afterburning of generator gas in additionally injected propellant, dynamic correlations are more complicated [6]. Above described feedback (1, 2, 3) and direct (4) connections exist in gas generator, which is of liquid-liquid scheme, and in the liquid stage of gas-liquid injector of the main combustion chamber. In gas-liquid injector, as it was described in [6], pulsation of combustion chamber pressure additionally influence or mixer by feedback

connection (7), if it exists in the injector, or gas site of the injector, (see Fig.1b) by means of feedback connection (6), and will excite pulsation in gas pipeline (8) or even influence the gas generator, which can response not only by mass flow pulsation, but also by temperature pulsation. The last ones will form feedback connections (9) and (10). Presence of the mixer will also arise feedback connections (12) and (13) that can organize their own self-oscillations in the mixer of gas-liquid injector. These pulsation of different origin can excite pulsation of heat release in the combustion zone and also can influence combustion oscillations parametrically (for instance, by pulsation of mean droplet diameter), or non-linearly, by changing mean efficiency of atomization and mixing [7]. From Fig 1c it became obvious that response of both jet and swirl injectors on pressure drop pulsation is rather strong.

So, previously performed studies [4-7] showed that from the position of automatical control theory, an injector is not only the device to prepare combustible mixture, but comprise simultaneously sensitive element, as it responds to pressure pulsation both from the combustion chamber and the feed system; an amplifier of pulsation; phase shifter and actuator. Amplification abilities of an injector are due to big difference between the pressure in the combustion chamber and the pressure drop, applied to the injector. Besides, injector can be a modulator of non-linear influence and a generator of self-oscillations [7].

2. Overview of stability development of F-1 injectors

Concerning the development of F-1 injector presented in [8], it is clear that next changes that provided stability of F-1 operation were used. First of all, placement of baffles attached to the injector fire face increased acoustic losses, mainly with the respect of first tangential and spinning modes of pulsation and practically eliminated the influence of tangential velocity on mixing of injected propellants. It was not enough to eliminate instability as amplitude of pressure self-oscillations decreased only to still high level of 65% from combustion chamber pressure; frequency lowered from 500 Hz to 400 Hz. Then, decreased angle of impingement of oxidizer sprays and decreased pressure drop applied to fuel channels of injector elements removed combustion zone down from the injector fire face, and more rough atomization elevated evaporation and burning time and so increased the thickness of the combustion zone. Such conditions according to [7] decreased the sensitivity of the combustion zone to any disturbances of pressure and propellants mass flow rate. However, some consequences of the injector development remained non-mentioned in [8]. There are changes in dynamic characteristics of injector elements, their response to pressure pulsation in the combustion chamber.

Jet injector elements, used in F-1, have rather simple dynamic characteristics, very close to plain inertial elements, described in [6]. Though response function of the injector in an engine to combustion chamber pressure pulsation depends also on dynamic characteristics of propellant feed lines, which are not evident now, let us approximately consider the absence of any shift angles applied by feed lines (which is possible in resonance conditions) and define only the influence of injector elements. In this case response of jet parts of injectors can be defined from equation 6 in [6] as a function of the

relation of pressure drop, applied to the jet part and combustion chamber pressure, and Strouhal number Shj = $\omega L_T/W_T$. For initial version of the injector, velocities of oxidizer and fuel are rather similar and therefore Sh_j values are equal. So, response functions and shift angles between mass flow rate and pressure pulsation are practically equal, though sensitivity of the injector element to combustion pressure pulsation will be rather high. In modified versions relation of oxidizer and fuel velocities are 3:1 to 4:1 [8]. Concidering equal length of O and F injector channels, they will have significantly different shift angles. Difference in pressure drop will define difference in amplitudes of mass flow responce. Both such factors will lead to the appearance of O/F ratio pulsation at the exit of the injector. Length of wave of such pulsation for rather low acoustic frequency f=500Hz will be about 32-50 mm and hardly will be mixed and dissipated by turbulent in-chamber flow. As to mass flow pulsation, it will be practically on the same level that in the initial case. So, new factor appeared: with presence of pressure pulsation, a lot of non-stoicheometric mixture appears in the combustion zone, the higher pressure amplitude, the higher growth of O/F coefficient amplitude. Mass flow rate pulsation is still high and in order to decrease pressure pulsation amplitude it is necessary to increase acoustic losses by means of baffles.

So, with the excitation of O/F pulsation, combustion chamber obtains additional non-linear feed back connection, decreasing sensitivity of the combustion zone to pulsation disturbances with the growth of pulsation amplitude and acting together with any other mechanism of high frequency instability.

3.Г. **Injector of Ox-rich staged combustion cycle engine combustion chamber**

3.1. Design features of the injector elements

Figs 4-6 present cross section views of typical combustion chamber injector elements: ignition sprayer, baffle injector element and main injector element. As to baffle one (Fig. 5), it comprise central gas propellant tube, covered by external spiral thread for fuel, which is already in super-critical state and serves additionally for regenerative cooling of external surface. Due to extremely long spiral passages, injector element is strongly damped and practically do not respond to pressure drop pulsation. More interesting is the main injection element (Fig. 6). It comprise open swirl injector for kerosene with profiled enlarged to its exit nozzle and two rows of inlet tangential channels, inlet part of the vortex chamber is connected with the acoustically tuned tube for gaseous propellant. Under excess pressure liquid enters the vortex chamber through tangential channels and forms hollow swirled flow inside, outflowing though the nozzle. Gas flow moves axially and atomize liquid film inside the vortex chamber and the nozzle. So, liquid atomization occurs in such type of injector element by means of formation of surface waves on the surface of rotating liquid film, stabilized by centrifugal forces on the wall, and tearing edges of these waves by gas flow (so called Helmholtz-Kelvin mechanism). Injector of this type consists from a gas pipe, usually with narrowed entrance to form an acoustic resonator for withdrawal of acoustic energy from the combustion zone to the gas manifold, and “opened” swirl injector, attached to the outflow edge of the gas pipeline and simultaneously serving as an atomizer and a mixer for oncoming liquid and gas flow.

If the size of the injector allows, gas pipeline and the vortex chamber of swirl injector are separated from each other by a collar to protect injected liquid flow from gas disturbance and to provide equal liquid distribution via angle of the flow. The length of the injector is usually tuned to withdraw maximum of acoustic energy from the combustion chamber. Length of the vortex chamber that is simultaneously a mixer is very significant as it defines atomization efficiency; a part of liquid propellant could be left in the form of thin liquid film that will create low temperature zone near by the fire face and protect it from excess overheating.

Advantages of such an injector are in low sensitivity of atomized liquid flow to combustion chamber pressure pulsation due to stabilization of liquid film on the wall of the injector.

Disadvantages of such an injector are in low atomization efficiency at low pressures but this parameter improves with pressure growth. So, such injectors found their usage in high pressure combustion chambers with ox-rich staged combustion cycle such as RD-170, RD-180 and some others [8].

3.2. Main injector operating parameters that define efficiency of preparation of combustible mixture.

3.2.1. Outflow operational parameters.

Quality of combustible mixture formation is defined by the specific mass flow rate distribution across and along the gained two phase flow, dispercity of droplets in this flow (usually it is characterized by mean droplet diameter $\boldsymbol{D_{32}}$ and spectrum of droplet sizes, dispersion coefficient), velocity field at the exit of the injector element, O/F ratio distribution in the combustible mixture flow. These values can be evaluated by CFD analysis, defined experimentally and approximately can be defined analytically, if the mechanism of atomization is known. Very significant for definition of these parameters is the velocity of atomization, that is atomized liquid mass flow rate per unit of liquid surface $\partial \boldsymbol{M}/\partial \boldsymbol{S}$.

According to the general atomization theory, for the Kelvin-Helmholtz atomization mechanism, the mean droplet diameter (neglecting liquid viscosity) can be defined as

$$(\boldsymbol{d}_{32})_{\mu=0} = \boldsymbol{C}_1 \frac{\sigma_l}{\rho_g (|\vec{\boldsymbol{U}}_g - \vec{\boldsymbol{U}}_l|)^2}, \quad (1)$$

where $\boldsymbol{C_1}$ is an empirical constant, and $|\vec{\boldsymbol{U}}_g - \vec{\boldsymbol{U}}_l|$ is the module of the vector difference between gas and liquid velocities. For shear coaxial injectors, $\boldsymbol{C_1} = 62$.

Taking into account the liquid viscosity μ_l,

$$d_{32} = (d_{32})_{\mu=0}\left[1 + C_2\left(\frac{\mu_l^2 \rho_g}{\sigma_l^2 \rho_l}\right)^{1/4} \cdot \left(\left|\vec{U}_g - \vec{U}_l\right|\right)^{1/2}\right], \qquad (2)$$

where C_2 is an empirical constant, and for shear coaxial injectors is equal to 0.035.

The mass flow rate of the atomized liquid per unit of liquid surface can be defined in the inviscid case as:

$$\left(\frac{\partial M}{\partial S}\right)_{\mu=0} = C_3\left|\vec{U}_g - \vec{U}_l\right|\sqrt{\rho_g \cdot \rho_l}\ , \qquad (3)$$

where C_3 is an empirical constant, and for shear coaxial injectors is equal to 0.17. Taking into account liquid viscosity will give:

$$\frac{\partial M}{\partial S} = \left(\frac{\partial M}{\partial S}\right)_{\mu=0} \cdot \left[1 + C_4\left(\frac{\rho_g}{\rho_l}\right)^{1/4} \cdot \left(\frac{\left|\vec{U}_g - \vec{U}_l\right| \cdot \mu_l}{\sigma_l}\right)^{1/2}\right] \quad , \qquad (4)$$

where C_4 is an empirical constant equal to –0.1 6 for shear coaxial injectors.

The aim of experimental research with basic injector is to verify if these constants are valid for atomization of liquid circular film and to define corrected values of C_1 through C_4.

Let us define the change in liquid film thickness due to atomization of liquid by gas flow. Approximately considering gas and liquid velocities to be constant along the mixing zone,

$$h_l = h_o - \frac{x\frac{\partial M}{\partial S}}{W_{al}\,\rho_l}\ , \qquad (5)$$

where h_o is the initial liquid film thickness, x is the variable length, and W_{al} is the axial velocity of liquid film. The length of the mixer filled by liquid film can be defined as the value of x where $h_l = 0$:

$$\frac{x}{h_o} = \frac{W_{al} \cdot \rho_l}{\partial M / \partial S}\ . \qquad (6)$$

d)0.0.| .– .• .◘ . ▯ @□@ Input operational parameters.

In order to define analytically output parameters, it is necessary to define input ones.

d) Physical parameters of propellants: density, viscosity, surface tension for liquid propellant, temperature, vapors pressure, possible supercritical conditions.
b) Mass flow rate per injector element.
c) Relative velocity of gas and liquid flows.
d) Pressures in feed lines and in the combustion chamber.

Physical parameters and pressures are or initially given or appears as a result of engine gas-thermodynamic calculation. As atomization zone of the injector element comprise low hydraulic resistance for strongly subsonic gas flow, gas velocity and mass flow rate in injector element can be defined by a standard procedure for subsonic gas flows [10]. As to liquid mass flow rate through the opened swirl injector, its amount with absence of the gas flow can also be defined with the help of classic swirl injector theory [11], by definition of its discharge coefficient and placing it in the Bernoulli equation, until assumptions of this theory (equality of axial velocity in the swirl nozzle to the velocity of surface waves propagation, conservation of momentum of movement along and across the liquid film) are valid. Presence of gas flow can change these conditions due to ejection of liquid into the gas flow, its atomization with consequent decrease of liquid film thickness along the vortex chamber. This problem is not yet totally studied, but test data showed that the effect is not high.

Strict definition of gas and liquid relative velocity is a complicated problem. The gas flow is breaking when spending a part of its kinetic energy for liquid atomization and droplet acceleration. Liquid film, differently from conditions in shear/coax injectors, is moving both in axial and circumferential directions. Therefore it is necessary to find the module of vector difference between axial gas flow and swirled liquid one. Numerical analysis showed that differently from simple subtraction in shear/coax case, vector difference showed much higher relative velocity for the same pressure drops and, consequently, more high atomization quality.

Liquid film thickness and its axial velocity even without gas flow influence will change via injector's mixer length under influence of centrifugal acceleration. In order to define the atomization velocity and liquid film thickness, it is necessary to know the initial values of these parameters without gas flow.

Here are some useful expressions for definition of liquid flow and its axial velocity in different parts of the vortex chamber and the nozzle of opened swirl injector, derived on the base of ideal swirl injector theory [11] with some additions from [1].

Radius of liquid vortex in the closed part of the vortex chamber, where $\boldsymbol{W_a} = 0$, is defined as:

$$\boldsymbol{r_{mk}} = \frac{(1-\varphi)\sqrt{2}}{\sqrt{2-\varphi}}\boldsymbol{R_n} = \boldsymbol{R_n}\sqrt{\boldsymbol{a}} \quad , \tag{7}$$

where $\boldsymbol{\varphi}$ is the relation of the nozzle area, filled by liquid, to the total nozzle area. It can be defined by the iteration procedure from the injector geometrical characteristic $\boldsymbol{A}$:

$$\boldsymbol{A} = \frac{(1-\varphi)\sqrt{2}}{\varphi\sqrt{\varphi}}, \tag{8}$$

where $A = \frac{R_{in} R_n}{n r_{in}^2}$ – un-dimensional criteria of similarity of a swirl injector outflow characteristics. Radius of liquid film in the nozzle r_{mn}:

$$r_{mn} = \sqrt{1-\phi} \cdot R_n \,. \qquad (9)$$

<u>Axial velocity in the nozzle</u> can be defined as:

$$W_{an} = \sqrt{\frac{\varphi}{2-\varphi}} \cdot W_{\Sigma}, \quad \textit{where} \;\; W_{\Sigma} = \sqrt{2\Delta p_{\Sigma} / \rho} \qquad (10)$$

<u>Circumferential velocity in the nozzle</u> is expressed by the equation

$$W_{un} = \sqrt{\frac{2(1-\varphi)}{(2-\varphi)}} \cdot W_{\Sigma} \qquad (11)$$

<u>Axial velocity in the vortex chamber</u> W_{av} and the corresponding radius of liquid vortex can be defined through the iteration procedure of solving the system of two equations (12 and 13):

$$W_{av} = \frac{\mu}{\overline{R}_v^2 - \overline{r}_{mv}^2} W_{\Sigma} \qquad (12)$$

and the corresponding value of the <u>liquid vortex radius</u> r_m:

$$r_m = \sqrt{\frac{a}{1-\overline{W}_{av}^2}} \cdot R_n \qquad (13)$$

<u>Circumferential velocity of the free surface</u> of the liquid vortex for ideal liquid can be defined from energy conservation equation:

$$W_{\Sigma}^2 = W_u^2 + W_a^2 + W_r^2 \qquad (14)$$

When $W_r = const$,

$$W_u^2 = W_{\Sigma}^2 \sqrt{1-\overline{W}_a^2} \qquad (15)$$

At the edge of the opened vortex chamber, centrifugal pressure of the rotating liquid film will be transformed in axial acceleration of the liquid flow and <u>axial velocity</u> will be increased:

$$W_{a_{ex}} = W_{an} \sqrt{3-2\varphi} \qquad (16)$$

<u>The radius of liquid film</u> will also be increased according to mass conservation equation:

$$r_{m_{ex}} = \sqrt{1 - \frac{\varphi}{\sqrt{3-2\varphi}}} \cdot R_n \qquad (17)$$

So, even without the influence of the gas flow, liquid film in the vortex chamber of opened swirl injector will be decreasing from the place of input channels towards the output edge.

Circumferential velocity of the liquid film at the exit of the swirl nozzle can be defined from momentum conservation equation as:

$$W_{u_{ex}} = W_{\Sigma} \frac{r_{m_{ex}}}{r_{mk}} \quad , \tag{18}$$

but as thin liquid film motion is accompanied by friction losses, circumferential velocity could be considered the same for all its thickness and equal to its value on the nozzle surface:

$$W_{u_{ex}} \approx W_{\Sigma} \sqrt{a} \tag{19}$$

Velocity of the liquid in tangential channels from classic theory is defined as:

$$W_{in} = W_{\Sigma} \frac{\sqrt{a}}{\overline{R}_{in}} \quad , \tag{20}$$

and the part of pressure drop, applied to tangential channels:

$$\Delta P_{in} = \Delta P_{\Sigma} \frac{a}{\overline{R}_{in}^2} \quad . \tag{21}$$

Expression (15) shows that differently from most of classical swirl injectors, the part of the pressure drop, applied to tangential channels of opened injector comprises the major part of the total pressure drop.

Angles of trajectories of liquid sprays to the axis of the injector can be defined as:

$$\alpha_l = \mathbf{arctan} \frac{W_u}{W_a} \tag{22}$$

For the nozzle

$$\alpha_n = \mathbf{arctan} \sqrt{\frac{2(1-\varphi)}{\varphi}} \tag{23}$$

Angle of spray at the edge of the nozzle, that is also equal to the half angle of liquid sheet after the nozzle, is approximately defined as:

$$\alpha_n = \mathbf{arctan}\sqrt{\frac{a}{1-a}} \tag{24}$$

As some of widely used swirl injectors (for example, RD-170 combustion chamber and gas generator) have divergent nozzles, there it is placed without derivation an expression for definition of the exit half angle of spray from injectors with such nozzles from [6]:

$$\alpha_{div} = \mathbf{arctan}\sqrt{\frac{a(1+q^2)}{\overline{R}_{ex}^2 - a}}\ , \tag{25}$$

where q is the tangent of angle of inclination of the nozzle wall exit to the axis of the injector, $\overline{R}_{ex} = \frac{R_{ex}}{R_n}$ - relation between the exit radius of the nozzle to its throat radius.

Thickness of liquid film in the divergent nozzle can be defined from the expression for

$$\varphi_{div} = \frac{\mu\sqrt{1+q^2}}{\sqrt{\overline{R}_{div}^2 - a}} = 1 - \frac{r_{m_{div}}^2}{R_{div}} : \tag{26}$$

$$h_{l_{div}} = R_{div}(1 - \sqrt{1-\varphi_{div}})\,. \tag{27}$$

So, we got all necessary expressions for liquid film thickness and components of its velocity definition.

3.3. Geometric parameters of injectors, significant for their operation

Actually, no insignificant geometric parameters exist in studied basic injector – every feature plays its role and causes some influence on injector operating parameters.

For liquid flow parameters as mass flow rate, components of velocity and film thickness – defining geometric parameters are the diameter of the vortex chamber/nozzle and area of inflow tangential channels. Most of liquid flow un-dimensional parameters are defined by geometrical characteristics of swirl injector A. (see 7-8). For opened swirl injector, let us transform the expression for A

$$A = \frac{R_{in}R_n}{nr_{in}^2} = \frac{\pi R_n R_n R_{in}}{\pi n r_{in}^2 R_n} = \frac{F_n}{F_{in}} \cdot \frac{R_{in}}{R_n} \tag{28}$$

The second part of the expression (28) is equal about unit, so liquid movement in opened swirl injector is mostly defined by the relation of its nozzle area to the area of inflow channels.

For gas flow – diameter of the inlet port and the diameter of the mixer are significant sizes as they define gas axial velocity along the swirled liquid flow. As the liquid surface opposed to the gas flow is much wider than in shear/coax injectors, velocity of atomization is high enough even with not so high gas velocity; no necessity to keep it too high as in shear/coax case, as it will decrease the efficiency of reverse flows of hot gases in the combustion chamber for stabilization of combustion. This outlet parameter of the injection process is a subject for CFD-optimization of processes in the combustion chamber.

For atomization and mixing – the presence of the collar, length of the mixer and its relation to mixer's diameter is significant. Not in every case the collar is used in the studied injector type. For small diameters of the gas stage of the injector, there is simply no space for a collar and plain step between the diameter of the gas pipe and liquid vortex chamber is enough to preserve liquid from the gas flow before it forms equal liquid vortex.

The length of the vortex chamber that also comprises atomizer and mixer with gas propellant is very significant. If it will be too long and liquid film will be totally atomized by the gas flow and will leave a part of mixer walls dry, the fire face of the injector assembly can be overheated and even burned by reverse flows from the combustion zone. If the mixer's length will be shorter than it is necessary to atomize all the fuel, a part of it will flow out from the injector edge and form conical liquid sheet that obviously will decrease mixing efficiency and completeness of combustion. The definition of the length of mixing zone by equation (5) is approximate: it does not take into account the stabilizing role of the injector's wall on liquid film atomization. Empirical constants in expressions (1-4) are still to be defined for this type of the injector. Until it will not be done, the choice of the mixer length will be a subject of fire test optimization.

Experimental research requires not so expensive and sophisticated optical and electrical measurements of liquid film length and thickness by any available method (partially such methods were described in [1] and [6]), and standard steady pressure and pressure drop measurements in pressurized test chamber. As the leading parameter for atomization is $\sqrt{\rho_g \rho_l}$, the usage of cold and dense gas will decrease requirements to pressure in it. As no measurements of two phase flow parameters are required, model transparent injector can be attached to the test chamber with no windows.

For acoustic tuning: significant parameters are total injector length and its relation with the length of acoustic wave in the gas flow inside the injector, and relation between the area of inlet port and the area of the rest injector gas channel. In acoustic sense, injector comprise not so simple device as a pure gas pipe. It begins from narrowing, have rather high velocity of the interior flow and have an atomizer at the exit, where gas flow is filled by plurality of small droplets. The last process will strongly decrease sound velocity in the flow and will cause additional losses of acoustic energy. So, exit of the injector cannot be considered as a pure open end.

Therefore, for confidence, it is worth to obtain experimental data for the impedance of the injector with the presence of the gas and atomized liquid flows to validate complicated but idealized acoustic equations presented in [6]. In order to do so, very simple equipment is to be used: pressure pulsation gages near the inlet and outlet of the injector (with accurate recording of the shift angle between signals) and the source of moderate gas pressure pulsation in the test chamber with tuned frequency to find out the amplitude-phase frequency characteristics of the injector. As no optical measurements are required, test chamber can be without windows, which simplify achievement of high pressure.

For liquid stage dynamic tuning, the most significant geometric parameter is the length of the vortex chamber, the place of surface waves propagation, phase shifter and integrator of liquid pulsation by gas flow. Dynamic characteristics of liquid stage also depend on the area and length of tangential channels and its distribution along the vortex chamber.

The number of rows of tangential channels and distance between them, related to the length of waves of disturbance propagation along the swirled liquid surface, are of great significance, as they can be used for mutual suppression of surface waves.

Dynamic characteristics of opened swirl injector are studied very poorly. Most of attention was paid for “classical” swirl injectors, predominantly used in many liquid rocket engines, all jet engines and in plurality of industrial applications. As for “open” injectors, they were considered to have very low response on pressure pulsation and therefore non-interesting for their dynamic characteristics study, as they hardly can be used as phase shifters or amplifiers to tune high frequency combustion instability and can only eliminate the instability mechanisms, joined with the injection and feed system. Their ability to serve as modulators of pulsation and servo-stabilizers was discovered only recently and not yet studied.

Thorough study of basic injector dynamic characteristics, the result of which will be the experimental response function of the injector to test chamber pressure pulsation, comprises measurements of gas steady and pulsation flow at the inlet of gas stage, pulsation velocity of the gas flow inside the injector and in the atomized flow at the exit and in free spray; liquid flow pulsation (pressure pulsation in the pre-injector cavity, velocity pulsation in a tangential channel, liquid film thickness fluctuations in the nozzle with variable pressure drop, pulsation frequency and different shapes of injector geometry. With the usage of the results of “classic” swirl injector experimental studies [1] and later works, the necessary addition for “open” injectors will be not so hard to get. The same equipment for exiting of pressure pulsation in liquid and gas flows with variable frequency may be used, as well as measurement gages for pulsation pressure, pulsed velocity in tangential passages and pulsed liquid sheet thickness in the vortex chamber. For two-phase flow pulsation measurements, contemporary optical methods may be used. For conditions of high test chamber pressure, very useful can be non-direct, electrical measurements of two-phase di-electrical penetrability, used in [6]. It measure actually the pulsation of local concentration of liquid phase in two-phase flow.

4. Dynamics of liquid injector stage.

4.1. Dynamics of classical swirl injector.

Response function of classical liquid swirl injector can be defined according to [1] as a combination of response functions of its parts:

$$\Pi_\Sigma = \frac{\boldsymbol{Q'_n} \ / \boldsymbol{Q_n}}{\Delta\rho'_\Sigma \ / \Delta\rho_\Sigma} = \frac{\boldsymbol{\overline{R}_v^2}}{\boldsymbol{a}} \cdot \frac{\Pi_{\boldsymbol{T}} \cdot \Pi_{\boldsymbol{vn}} \cdot \Pi_{\boldsymbol{n}}}{\boldsymbol{2}\Pi_{\boldsymbol{T}} \cdot \Pi_{\boldsymbol{vc}} + \boldsymbol{1}}, \tag{29}$$

where $\boldsymbol{\Pi_T}$ is a complex response function of tangential channels as an inertial element:

$$\Pi_{\boldsymbol{T}} = \frac{\boldsymbol{Q'_T}}{\boldsymbol{Q_T}} / \frac{\Delta \boldsymbol{p'_T}}{\Delta \boldsymbol{p_T}} = \frac{\boldsymbol{1}}{\boldsymbol{2}} \cdot \frac{\boldsymbol{1 - Sh_T}}{\boldsymbol{1 + Sh_T^2}}, \tag{30}$$

$\boldsymbol{Sh}$ is Stroughal number for tangential channels, $\boldsymbol{Sh_T} = \frac{\boldsymbol{\omega L_T}}{\boldsymbol{W_T}}$,

$\boldsymbol{L_T}$ is the length of tangential channel,
$\boldsymbol{W_T}$ is the velocity of liquid inside tangential channels.

$\boldsymbol{\Pi_{vn}}$ is the complex response function of the vortex chamber. It comprises un-dimensional volumetric flow rate pulsation in the vortex chamber near the nozzle, related to un-dimensional velocity or volumetric flow rate pulsation in tangential channels:

$$\Pi_{\boldsymbol{vn}} = \frac{\boldsymbol{Q'_{vn}}}{\boldsymbol{Q_{vn}}} / \frac{\boldsymbol{Q'_T}}{\boldsymbol{Q_T}} \tag{31}$$

The value of $\boldsymbol{\Pi_{vn}}$ is defined in vortex chambers of classic swirl injectors by surface waves reflection from the nozzle and depends on the reflection coefficient of the swirl injector nozzle and Stroughal number of the vortex chamber $\boldsymbol{Sh_{vc}} = \frac{\boldsymbol{\omega L_{vc}}}{\boldsymbol{W_W}}$, where $\boldsymbol{W_W}$ is the velocity of waves propagation in the vortex chamber

$$\boldsymbol{W_W} = \sqrt{\frac{\boldsymbol{1}}{\boldsymbol{2}}\left(\frac{\boldsymbol{\overline{R}_v^2}}{\boldsymbol{a}} - \boldsymbol{1}\right) + \frac{\boldsymbol{\mu}}{\boldsymbol{\overline{R}_v^2 - a}}} \quad . \tag{32}$$

$\boldsymbol{\Pi_{vn}}$ can be analytically defined by the solution of the wave equation [6] of the vortex chamber with boundary conditions at the entrance (tangential channels) and at the exit (nozzle), or approximately, by iteration of the surface waves according to the engineering method described in [1].

Π_n is a complex response function of the nozzle and comprise the relation between volumetric flow rates of liquid at the nozzle exit to the connection of the vortex chamber to the nozzle:

$$\Pi_n = \frac{Q'_n}{Q_n} / \frac{Q'_{vn}}{Q_{vn}} . \tag{33}$$

Π_n reflects the role of a nozzle as a transport element and takes into account the reflection coefficient Π of surface waves from the nozzle and decreasing of waves amplitude due to viscous losses:

$$\Pi_n = (1 - \Pi) e^{-\Psi_n (i + \upsilon/2\pi)} . \tag{34}$$

Π_{vc} is the response function of the closed end of the vortex chamber and comprise a feed back connection between surface waves in the vortex chamber that excite centrifugal pressure pulsation which influences the outlet of tangential channels:

$$\Pi_{vc} = \frac{\Delta p'_{vc}}{\Delta \rho_T} / \frac{Q'_T}{Q_T} \tag{35}$$

Π_{vc} comprises the vector sum of ***Π_{v2}*** and ***Π_{v3}*** due to existence of two mechanisms of pulsation transportation along the vortex: by means of surface waves and by means of waves of vorticity.

$$\Pi_{v2} = \overline{\Omega}_\infty \left(\mathbf{Re}\, \Omega_{vk} + i\, \mathbf{Im}\, \Omega_{vk} \right) , \tag{36}$$

where $\overline{\Omega}_\infty$ is un-dimensional amplitude (related to the radius of liquid surface) of surface waves in infinitely long vortex chamber, $\Pi_{v2} = \overline{\Omega}_\infty \left(\mathbf{Re}\, \Omega_{vk} + i\, \mathbf{Im}\, \Omega_{vk} \right)$

$$\overline{\Omega}_\infty = \frac{1}{A\sqrt{2(\overline{R}_v^2 - a)}} \cdot \left| \frac{W'_{in}}{W_{in}} \right| , \tag{37}$$

$\mathbf{Re}\, \overline{\Omega}_{vk}$ and $\mathbf{Im}\, \overline{\Omega}_{vk}$ are results of surface waves summarizing in the closed end of the vortex chamber.

Usually, determination of ***Π_{v3}*** is the most complicated place in swirl injector dynamics as it strongly depends on radial velocity in the vortex chamber, via which excitations of vorticity are spread in the closed section of the vortex chamber. For classic swirl injector with long enough vortex chamber, the solution was found in [1] and can be numerically calculated:

$$\Pi_{v3} = \frac{\Delta \overline{P}'_{v3}}{2\overline{W}'_{in}} = \int_0^1 \frac{e^{i\left[\omega t - \frac{\omega R_{in}}{W_\Sigma} \cdot \frac{\overline{R}_v^2}{\mu} \cdot \overline{x} tg \frac{\pi \overline{x}}{2}\right]}}{\left[1 - \frac{(\overline{R}_v^2 - \sqrt{a})\overline{x}}{\overline{R}_v}\right]^3} d\overline{x} . \tag{38}$$

Other shapes of injectors will require to find corresponding $\boldsymbol{\Pi_{v3}}$ depending on radial velocity distribution.

The final amplitude-phase diagram of the response function of classical swirl injector in presented in [6]. Classical swirl injector in general case comprises a combination of inertial elements (tangential channels), capacitance (vortex chamber) and transport element (nozzle). Vortex movement of liquid serves as a memory sell, as liquid vortex responds by centrifugal acceleration fluctuations on velocity pulsation in tangential channels, that were several periods ago. In general case it is rather sensitive but has ability to become a damper or a filter of pulsation according to [5].

4.2. Peculiarities of injector dynamics of "open" swirl injector.

Expression (29), which reflects the method of frequency characteristics widely used in automatic control theory, is valid for definition of dynamic characteristics of "open" injector.

4.2.1. Dynamics of tangential channels can be defined according to the expression (30). Numerical difference between $\boldsymbol{\Pi_T}$ for classic swirl injector and for "open" injector will be in less value of Strouhghal number $\boldsymbol{Sh_T}$ due to higher velocity in tangential channels, defined by the equation (20). In "open" case, $\overline{\boldsymbol{R}}_{in}$ is near by 1, and $\overline{\boldsymbol{W}}_T$ will totally depend on $\boldsymbol{a = f(A)}$.

4.2.2. Response functions $\boldsymbol{\Pi_{vn}}$ and $\boldsymbol{\Pi_n}$ will coincide as it is no definite separation between vortex chamber and the nozzle. Due to the absence of reflected waves (no nozzle, no reflection), module of $\boldsymbol{\Pi_{vn}}$ will be equal to 1, and $\boldsymbol{\Pi_n}$ can be calculated according to (34) with the value of the reflection coefficient $\mathbf{\Pi} = 0$.

4.2.3. Feedback connections of the vortex chamber with tangential channels, described for classic swirl injector by the sum of two response functions $\boldsymbol{\Pi_{v2}}$ and $\boldsymbol{\Pi_{v3}}$ are also strongly simplified in "open" swirl injector. $\boldsymbol{\Pi_{v2}}$ has no influence of reflected waves and therefore will be co-phase with $\overline{\boldsymbol{W}}'_T$, its module will not depends on frequency:

$$\overline{\Omega}_\infty = \frac{1}{A\sqrt{2(1-a)}} \cdot \left|\frac{W'_{in}}{W_{in}}\right| \quad . \tag{39}$$

Corrections of $\overline{\Omega}_\infty$ value due to the influence of axial velocity in the vortex chamber, which are insignificant in classic swirl injectors, become rather big in "open" ones:

$$\Omega^*/\Omega = \sqrt{\frac{\left(\overline{R}_v^2 - a\right)^3}{\left(\overline{R}_v^2 - a\right)^3 + \mu}} \tag{40}$$

and decrease the amplitude several times , depending on $\boldsymbol{A}$. So, the influence of $\boldsymbol{\Pi_{v2}}$ will be very low and can be ignored in further analysis.

As to $\boldsymbol{\Pi_{v3}}$, it is not necessary any more to integrate circumferential velocity pulsation across the liquid film layer, as the thickness of the liquid film is low and comparable to the diameter of tangential channels, wherefrom it can be considered that the whole thickness of the liquid film in inflow section is swirled synchronously with the velocity pulsation in tangential channels. So, the first, described in [1], quasi-stationary model can be used:

$$\boldsymbol{K = \frac{\Delta P'_{vk} \Big/ \Delta P_{vk}}{W'_T \Big/ W_T} = 1; K_\Sigma = \frac{\Delta P'_{vk} \Big/ \Delta P_\Sigma}{W'_T \,/\, W_\Sigma} = \frac{\overline{R}_v^2 - a}{a}} \quad . \tag{41}$$

So, the definition of $\boldsymbol{\Pi_{v3}} = \boldsymbol{\Pi_{v1}}$ is also strongly simplified.

4.2.4. Additional response function of vortex chamber/nozzle appears in the expression (29) due to realization of the mechanism of vorticity waves propagation in longitudinal direction. The early works on swirl injector dynamics , such mechanism was described by F.M. Tiniakov, but later it was ignored as in real swirl injector of classic shape, mainly used in liquid rocket engines, the length of longitudinal waves of vorticity is very small (in the order of parts of a millimeter) due to low axial liquid velocity, they quickly dissipate and do not reach the nozzle entrance. Not so with “open” injectors, where axial velocity of liquid for the most part of the vortex chamber is equal to the velocity of surface waves propagation. Though this mechanism and its interaction with the mechanism of surface waves propagation is very poorly studied, in real “open” swirl injectors it can be totally excluded by means of usage of two rows of tangential channels, the distance between which is equal to the half of length of vorticity pulsation wave. The axial velocity of liquid between rows of tangential channels is approximately twice less than in the rest of vortex chamber, and liquid film thickness is maximal. For basic injector, this velocity value is about 8.5 m/sec; so for main chamber frequency of 1700Hz, the half wave length is about 5 mm. For another frequencies, the effect of vorticity waves must be studied.

Theoretically, the presence of at least two mechanisms of volumetric flow rate pulsation propagation with different axial velocities and equal amplitudes gives the possibility of total suppression of mass flow rate pulsation at the edge of swirl injector nozzle with properly chosen nozzle length. Such idea was realized in classic swirl injector by placing a row of income tangential channels in some distance from the closed end of the vortex chamber [12], and by manufacturing of two rows of tangential channels with the distance between them, equal to the half length of the wave of disturbance propagation [13]. “Open” swirl injectors are more useful for such idea realization as axial velocity of disturbances propagation in them is much less than surface waves velocity, so they can be more compact.

Analytical definition of proper length of “open” injector vortex chamber is not so simple, as velocities of both mechanisms of disturbances propagation are changed via nozzle length: surface waves velocity decreases with the thickness of liquid film and losses of

circumferential velocity and its centrifugal acceleration, according to $\sqrt{h_L \cdot j}$, and waves of vorticity, visa versa, will accelerate when moving towards the edge of the nozzle proportionally with the axial velocity of liquid.

The final expression for the response function of "open" swirl injector will comprise:

$$\Pi_{\Sigma_{open}} = \frac{Q_n' \ / Q_n}{\Delta\rho_\Sigma' \ / \Delta\rho_\Sigma} = \frac{1}{a} \cdot \frac{\Pi_T \cdot (\Pi_{n1} + \Pi_{n2})}{2\Pi_T \cdot \Pi_{v1} + 1} \tag{42}$$

where Π_{n1} and Π_{n2} are response functions of the vortex/nozzle for waves of vorticity and surface waves, Πv1 is the feedback connection according to the first model [1]. Vector diagram is strongly simplified before the vector diagram of classic swirl injector in [6]. Pulsation of $\Delta P_v'$ is co-phase with the velocity pulsation in tangential channels $\overline{W_T'}$ and total shift angle of the injector Ψ_Σ comprises a pure sum of $\Psi_T + \Psi_n$. Sensitivity of "open" swirl injectors to pressure drop pulsation oscillation even when neglecting possible self-suppression of pulsation in the nozzle by two mechanisms its propagation is much less than by normal classic swirl injector and can be defined by relation of modules of vectors $\vec{Q}_n'$ and $\Delta\vec{P}_\Sigma'$. The influence of vorticity waves propagation in axial direction is still to be studied, but empirical experience showed very strong effect. For main combustion chamber injector it may be insignificant as practically all liquid from liquid vortex will be atomized by gas flow, but for liquid-liquid gas generator injectors it will be very significant and worth to be studied. Expected length of the vortex chamber that will suppress flow pulsation can be defined from its Stroughal number $Sh = L_n/\lambda_w$, for basic injector L_n is about 20 mm.

5. Dynamics of atomization and mixing

5.1 Effect of liquid flow pulsation.

Cooperation of the liquid film along the gas flow will be characterized by simultaneous atomization of liquid portions, injected in different time and having different mass flow rates, corresponding to the moment of their injection in the vortex chamber. The result of such interaction will be in strong decrease of the response function module via growth of Stroughal number of the mixing zone $Sh_m = \omega L_n/W_{al}$. This influence reminds the mechanism of flow pulsation integration during combustion, described in [6], and can provide total insensitivity of the injector to any pulsation of liquid flow. This promising possibility is worth to be studied experimentally and analytically.

5.2 . Effect of gas flow pulsation.

Gas flow pulsation will excite pulsation of atomized liquid. According to [7], total sensitivity of the injector to gas pulsation will be defined as:

$$\left|\Pi_{ag}(\omega)\right| = \frac{\beta\omega L_{vc}}{3W_g} \quad , \tag{43}$$

where β is a degree coefficient in the expression of atomization velocity ; usually it is less then unit and depends on the mechanism of atomization. As gas velocity is much higher than axial velocity of the liquid, response of atomized mass flow rate will be rather low. Not so with the sensitivity of gas flow in injector, which is sufficient. Therefore, under the influence of pressure disturbances in the combustion chamber, injector will generate pulsation of O/F ratio. Such non-stoicheometric composition will burn for more long time and occupy more length of the combustion chamber. The sensitivity of the combustion zone to any fluctuations of mass flow rate and combustion chamber pressure will be decreased. So, the studied injector is expected to comprise not only linear damper and suppressor of liquid flow pulsation, but also as non-linear servo-stabilizer of the operational process. The process of atomization of liquid film, stabilized by vortex chamber walls, is one of the most stable with the respect of self-oscillations formation.

6. Conclusions

1. Modified injector elements of F-1 engine with excitation of combustion pressure pulsation produced pulsation of O/F ratio that can be additional stabilization factor in decreasing of combustion process sensitivity to any disturbances in the combustion chamber.
2. Studied type of gas-liquid injector is expected to be the most insensitive to pressure and velocity pulsation in the combustion chamber between other types.
3. It do not produce dangerous self-oscillations, nor it is sensitive to pressure drop pulsation, applied to liquid propellant injector stage.
4. Gas part of the injector comprises an acoustic resonator tuned to withdraw a significant part of acoustic energy from the combustion chamber to the gas manifold, where it is to be dissipated by perforated plates.
5. Liquid atomization for high gas densities is efficient and uses rotating liquid surface, stabilized on walls of the injector by centrifugal forces, that provides absence of rough droplets, equal atomization and even mixing.
6. Remained liquid film protects fire face of the injector assembly from overheating.
7. Ability to enlarge the thickness of the combustion zone while amplitude of pressure drop pulsation grows makes this injector be able to servo-stabilize instability of combustion.
8. As some of principal stationary and dynamic characteristics of basic gas-liquid injector still remain uncertain, it is worth while to organize an experimental and analytical research of its yet unstudied parameters to be able to compose the reliable method of the injector design (see the Application).

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Figures

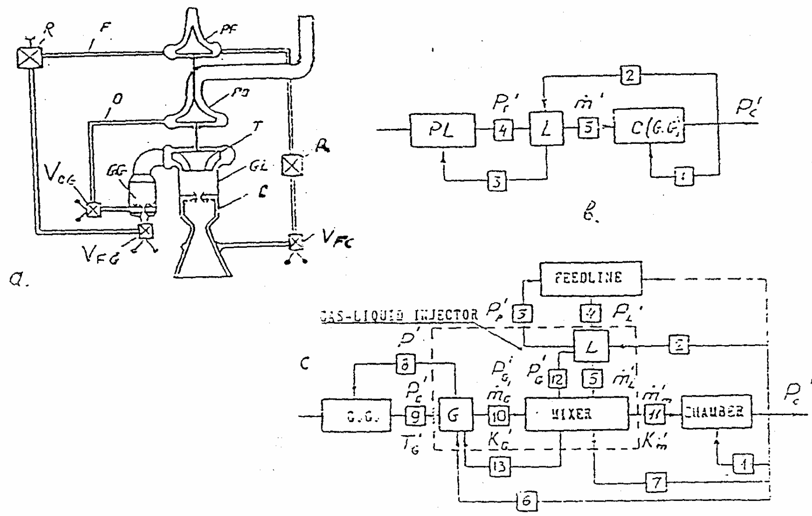


Fig.1 Block-diagram of LRE and interaction of the dynamic processes running in it: a) pneumatic and hydraulic diagram; b) interaction of processes in LRE of the open configuration; c) interaction of the processes occurring in LRE with generator-gas afterburning.

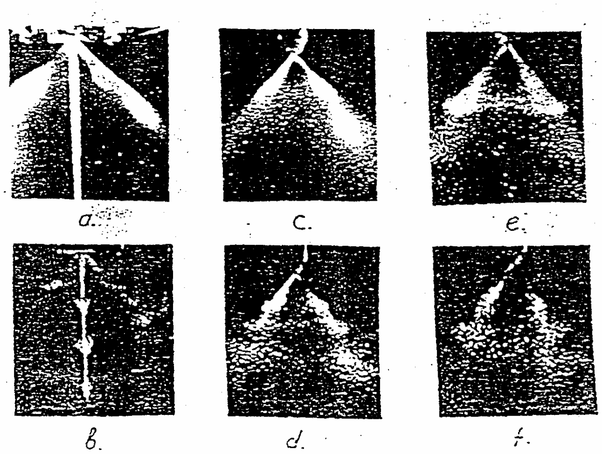


Fig2. Photographs of hollow spray-swirl (a, b) and swirl (c-f) injectors under stationary (a, c) and dynamic (b, d, e, f) conditions: a) ΔP = 0.6 MPa; b) ΔP = 0.45 MPa, f = 1100 Hz; c) ΔP = 0.51 MPa; d) ΔP = 0.405 MPa, f = 1200 Hz; e) ΔP = 0.41 MPa, f = 1006 Hz; f) ΔP = 0.2 MPa, f = 560 Hz, $\left|\Delta P'\right|$ = (0.2 ... 0.22) ΔP

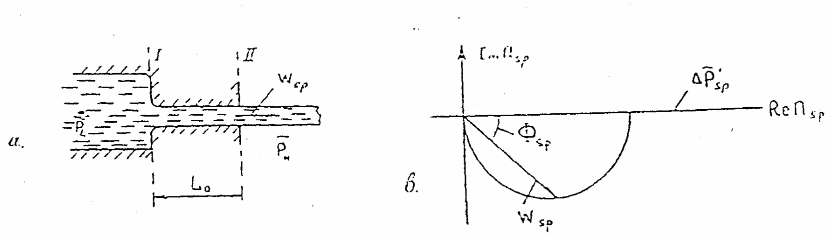
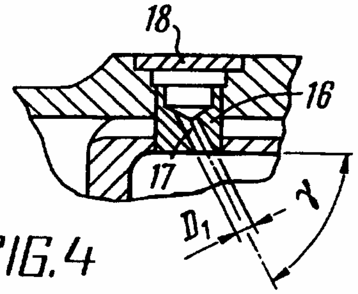


Fig.3 Flow diagram and phase-amplitude and vector diagrams of the spray injector



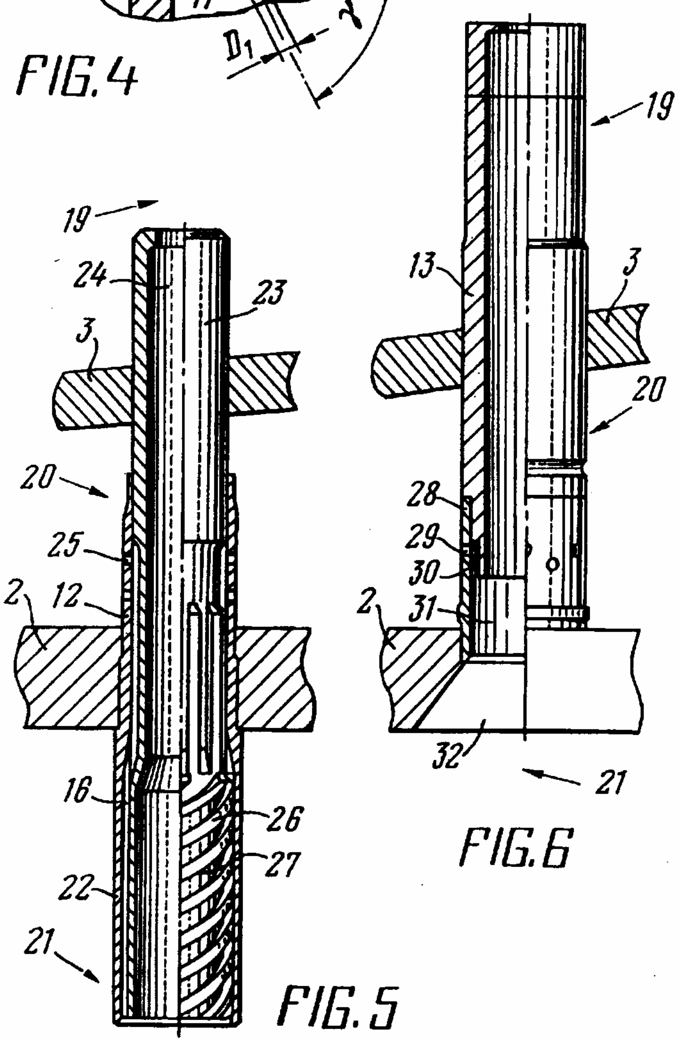


Fig. 4-6. Basic gas-liquid injector elements from US Patent # 6244041